

Collisions of Small Nuclei in the Thermal Model

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* Presented at Critical Point and Onset of Deconfinement CPOD2016, University of Wrocław, Poland , May 30th - June 4th 2016

An analysis is presented of the expectations of the thermal model for particle production in collisions of small nuclei. The maxima observed in particle ratios of strange particles to pions as a function of beam energy in heavy ion collisions, are reduced when considering smaller nuclei. Of particular interest is the Λ/π^+ ratio shows the strongest maximum which survives even in collisions of small nuclei.

PACS numbers: 25.75.-q, 25.75.Dw, 13.85.Ni
September 14, 2016

1. Introduction

A large effort is presently under way to study not only heavy- but also light-ion collisions. This is being motivated by the results obtained in heavy ion collisions like Pb-Pb and Au-Au, for the K^+/π^+ , and also other particle ratios. It has been conjectured that these indicate a phase change in nuclear matter [1].

A consistent description of particle production in heavy-ion collisions, up to LHC energies, has emerged during the past two decades using a thermal-statistical model (referred to simply as thermal model in the remainder of this talk). It is based on the creation and subsequent decay of hadronic resonances produced in chemical equilibrium at unique temperature and baryon chemical potential. According to this picture the bulk of hadronic resonances made up of the light flavors u,d and s valence quarks are produced in chemical equilibrium.

Indeed some particle ratios exhibit very interesting features when studied as a function of the beam energy which deserve attention: (i) a maximum in the K^+/π^+ ratio, (ii) a maximum in the Λ/π ratio, (iii) no maximum in the K^-/π^- ratio. The maxima occur at a center-of-mass energy of around 10 GeV [2, 3, 4]. It is interesting to note that the occurrence of these maxima happens in an energy regime where a maximum baryon density occurs [5] and a transition from baryon-dominated freeze out to a meson dominated one takes place [4]. An alternative interpretation is that these maxima reflect a phase change [1] to deconfined state of matter.

The maxima mark a distinction between heavy-ion collisions and p-p collisions as they are not observed in the latter. This shows a clear difference between the two systems which is worthy of further investigation.

It is the purpose of the present talk to report on an analysis [6] studying the transition from a small system like a p-p collision to a large system like a Pb-Pb or Au-Au collision and to follow explicitly the genesis of the maxima in certain particle ratios.

2. The model

A relativistic heavy-ion collision will go through several stages. At one of the later stages, the system will be dominated by hadronic resonances. The identifying feature of the thermal model is that all the resonances as listed by the Particle Data Group [7] are assumed to be in thermal and chemical equilibrium. This assumption drastically reduces the number of free parameters and thus this stage is determined by just a few thermodynamic variables namely, the chemical freeze-out temperature T , the various chemical potentials μ determined by the conserved quantum numbers and by the volume V of the system. The latter plays no role when considering ratios of yields. It has been shown that this description is also the correct one [8, 9, 10, 11] for a scaling expansion as first discussed by Bjorken [12].

In general, if the number of particles carrying quantum numbers related to a conservation law is small, then the grand-canonical description no longer holds. In such a case conservation of quantum numbers has to be implemented exactly in the canonical ensemble [13, 14]. In the case considered here there are two volume parameters: the overall volume of the system V , which determines the particle yields at fixed density and the strangeness correlation (cluster) volume V_c , which reflects the canonical suppression factor and reduces the densities of strange particles. Assuming spherical geometry, the volume V_c is parameterized by the radius R_C which serves as a free parameter and defines the range of local strangeness equilibrium.

3. Origin of the maxima

According to the thermal model, the baryon chemical potential decreases continuously with increasing beam energy. At the same time the temperature increases rather quickly until it reaches a plateau. Following the rapid rise of the temperature at low beam energies, the Λ/π^+ and K^+/π^+ also increase rapidly. This halts when the temperature reaches its limiting value. However, simultaneously the baryon chemical potential keeps on decreasing. Consequently, the Λ/π and K^+/π^+ ratios follow this decrease due to strangeness conservation as K^+ is produced in associated production together with a Λ . The two effects combined lead to maxima in both cases. For very high energies, the baryo-chemical potential no longer plays a role ($\mu_B \approx 0$) and the temperature is constant hence these ratios hardly vary [4].

To show this in more detail we present as an example in Fig. 1 lines where the K^+/π^+ and the Λ/π^+ ratios remain constant in the $T - \mu_B$ plane. It should be noted that the maxima of these ratios do not occur in the same position, which remains to be confirmed experimentally. It is also worth noting that the maxima are not on but slightly above the freeze-out curve.

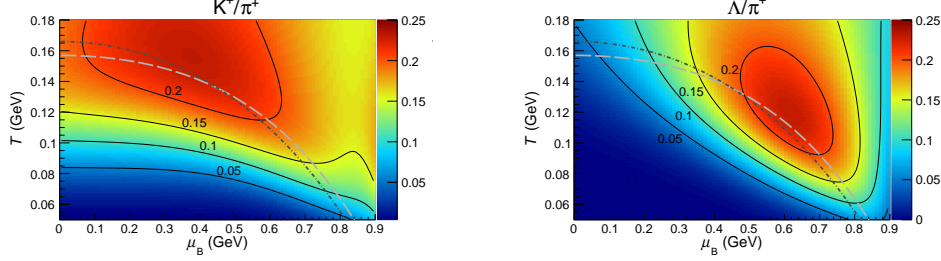


Fig. 1: Values of the K^+/π^+ (left-hand pane) and the Λ/π^+ (right-hand pane) ratios in the $T - \mu_B$ plane. Lines of constant values are indicated. The dashed-dotted line is the freeze-out curve obtained in [3] while the dashed line uses the parameterization given in [18]. Note that the maxima do not occur in the same position.

4. Particle ratios for small systems

To consider the case of the collisions of smaller nuclei we have to take into account the strangeness suppression according to the canonical model, i.e. the concept of strangeness correlation in clusters of a sub-volume $V_c \leq V$ [15, 16, 17].

A particle with strangeness quantum number s can appear anywhere in the volume V but it has to be accompanied by another particles carrying strangeness $-s$ to conserve strangeness in the correlation volume V_c . Assuming spherical geometry, the volume V_c is parameterized by the radius R_C which is a free parameter that defines the range of local strangeness equilibrium.

In the following we show the trends of various particle ratios as a function of $\sqrt{s_{NN}}$. The dependence of T and μ_B on the beam energy is taken from heavy-ion collisions [3]. For p-p collisions slightly different parameters are more suited [19]. Therefore, the calculations shown give the general trend. We have ignored the variations of other parameters with system size.

We focus on the system-size dependence of the thermal parameters with particular emphasis on the change in the strangeness correlation radius R_C . The parameters $R = 10$ fm (which is the value for central Pb-Pb collisions) and $\gamma_S = 1$ are kept fixed. The freeze-out values of T and μ_B will vary with the system size [17], however this has not been taken into account in the present work which aims to give a qualitative description of the effect.

The smaller system size is described by decreasing the value of the correlation radius R_C . This ensures that strangeness conservation is exact in R_c , and that strangeness production is suppressed with decreasing R_c .

In Fig. 2 we show the energy and system size dependence of two particle ratios calculated along the chemical freeze-out line. In Fig. 2 a maximum is

seen in the K^+/π^+ ratio which gradually disappears when the correlation radius decreases. A different effect is seen in Λ/π^\pm ratio. Here, the gradual decrease of the maximum is also seen but, contrarily to the K^+/π^+ ratio, it remains quite prominent even for a small correlation radius. Also, the maximum shifts, for smaller systems, towards higher $\sqrt{s_{NN}}$. For pp collisions which correspond to a R_C of about 1.5 fm [17], they will hardly be observed. It should also be noted that in the thermal model the maxima happen at different beam energies.

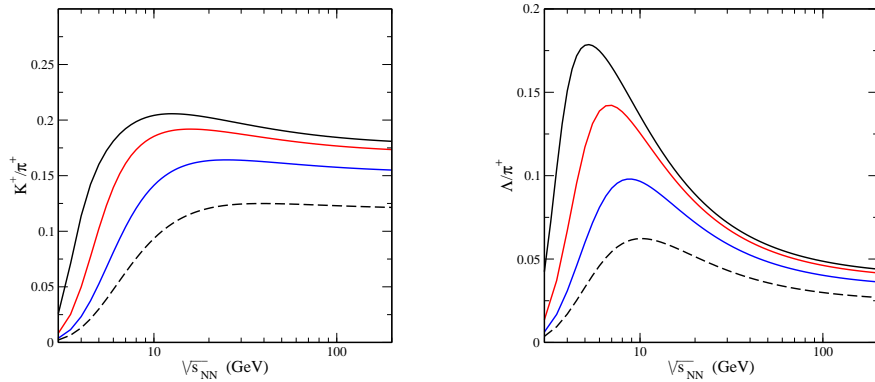


Fig. 2: Values of the K^+/π^+ (left-hand pane) and the Λ/π^+ (right-hand pane) ratios as a function of invariant beam energy for various strangeness correlation radii R_c , calculated using the thermal model[20]. The correlation radius is varied from 3.0 (top curve) to 2.5, 2.0, 1.5 and finally 1.0 fm (bottom curve). Note that the Λ/π^+ ratio is the ratio where the maximum stays most pronounced as the system size is reduced.

It must be emphasized that the results presented here are of a qualitative nature. In particular there could be changes due to variations with the system size of the temperature and the baryon chemical potential. In addition the strangeness equilibration volume V_c could be energy dependent and system size dependent.

5. Conclusions

The thermal model qualitatively describes the presence of maxima in the K^+/π^+ and the Λ/π^\pm ratios at a beam energy of $\sqrt{s_{NN}} \approx 10$ GeV. In this talk we have described what could possibly happen with different strange particles and pion yields in collisions of smaller systems due to constraints imposed by exact strangeness conservation. In particular, the Λ/π^+ ratio still shows a clear maximum even small systems. The pattern of these maxima is also quite special as they are not always at the same beam energy.

Acknowledgments

K.R. acknowledges the supported by the National Science Center, Poland under grant Maestro, DEC-2013/10/A/ST2/00106

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